

## COMMENTARY

# Plant Biology Research Comes of Age in China

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A modern plant biology research enterprise is developing rapidly in mainland China. The cohort of well-trained young scientists has expanded, the prevalence of international research collaborations has risen, and the number of publications in international journals has surged over the past 10 years. In stark contrast with its limited contribution over the decades prior to 1990, China's plant biology research enterprise is more productive and internationally connected today than ever before. This trend is perhaps most apparent in China's growing representation in international journals. Here, we trace how early roots and recent reforms have laid the foundation for the development of mainland China's plant biology research enterprise and explore some of the present challenges.

Overall, the number of annual publications by mainland China's plant scientists in a sample of major plant-specific and general scientific journals has increased dramatically over the last 15 years, from two publications in 1991 to 61 in 2005 (Figure 1A). This upward trend has been particularly prominent since 2002. China's share of total Asian publications in *The Plant Cell*, *The Plant Journal*, and *Plant Physiology* has also grown to >20%, a dramatic increase over the previous decade (Figure 1B). However, trends in publication numbers offer only a partial glimpse of the progress that has followed broader changes in China's research environment

over the past two decades. China's broad-based reform program in the late 1970s focused on revitalizing the nation's science and technology by increasing research funding and reforming institutional arrangements. With broad-based support from the government, many institutions have steadily hired new personnel and upgraded equipment and facilities. A growing number of these recruits are returning scientists trained abroad and have brought with them expertise and valuable overseas connections. These stronger international ties and China's internal experimentation with new institutional models are catalyzing fundamental changes in China's research environment.

## EARLY ROOTS OF PLANT BIOLOGY IN CHINA

Modern plant biology research in China started in the 1930s, when overseas plant biologists Pei-sung Tang (trained in the U.S.) and Tsung-Le Loo (trained in Japan) returned to China and set up research and training programs in plant biology. For Tang, the program was first established at Wuhan University but influenced the later development of similar programs at other prominent universities, including National Southwest Associated University, Tsinghua University, China Agricultural University, the Chinese Academy of Sciences (CAS), Fudan University, and Peking University. His research spanned a number of areas, including plant respiration and energy production (Tang, 1981), plant hormonal action, and induction of polyploidy

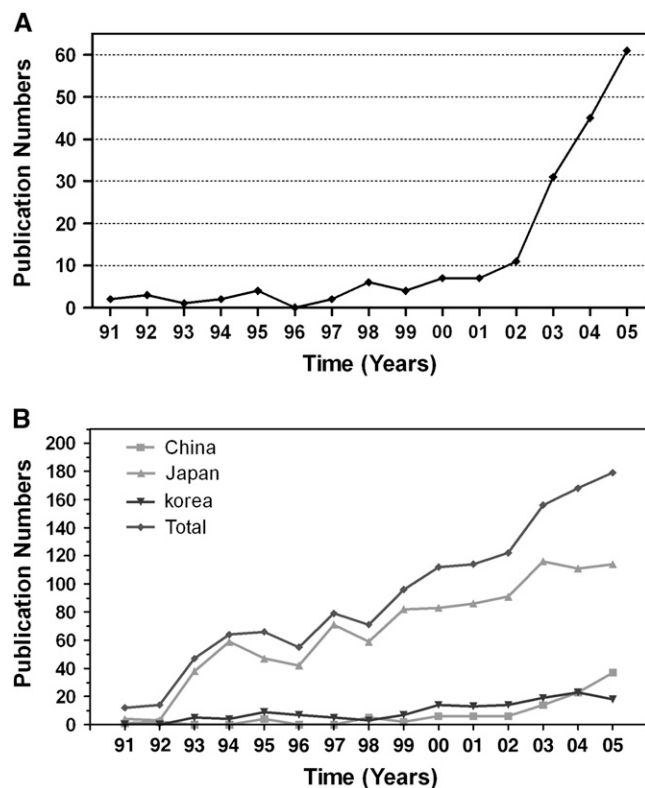
(Tang and Loo, 1940). He was the first to reveal inducible activity of a nitrate reductase in rice seedlings (Tang and Wu, 1957; Tang, 1983). Over more than 30 years (1933 to 1965), Dr. Tang and his associates published a large number of articles in plant biology research, including two in *Nature* (Chen et al., 1945; Tang and Wu, 1957) and one in *Science* (Tang and Loo, 1940).

Around the same time, Hung-chang Yin made strides in plant biology research, especially on the mechanism of chloroplast photosynthetic energy conversion, which was reported successively in two publications in *Science* (Yin and Sun, 1947; Yin and Tung, 1948). A group of researchers slightly junior to Tang, Loo, and Yin actively pursued basic research in plant biology, and at least four other prominent plant biologists emerged during this period: S.W. Loo (Tang and Loo, 1940; Loo and Wang, 1943), C.H. Lou (Lou, 1945; Hsueh and Lou, 1947), T.H. Tsao, C. Tsui (Tsui, 1949), and C.Y. Wong (Wong, 1939). These scientists helped to train a new generation of younger researchers, many of whom have mentored or are currently mentoring today's crop of aspiring plant biologists. Zhihong Xu, the current president of Peking University and a noted plant biologist, was among those young students in the early 1960s.

## REFORM AND OPENING: SEEDS FOR CONTEMPORARY PLANT BIOLOGY IN CHINA

China's program of reform and opening to the world in the late 1970s marked an

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**Figure 1.** Increases in Plant Biology Publications in China.

**(A)** Annual numbers of plant biology publications originating from China from 1991 to 2005, based on a sample of 14 representative journals that included *The Plant Cell*, *The Plant Journal*, *Plant Physiology*, *Plant Molecular Biology*, *Nature*, *Nature Genetics*, *Nature Biotechnology*, *Science*, *Cell*, *Genes and Development*, *Current Biology*, *PNAS*, *Nucleic Acids Research*, and *Development*.

**(B)** Research articles in three major plant biology journals (*Plant Cell*, *Plant Journal*, and *Plant Physiology*) from Asia and the three representative countries (China, Japan, and Korea) during the last 15 years. In the legend, "Total" indicates the total number of publications from China (mainland), Japan, South Korea, Singapore, and Taiwan.

important turning point for the sciences in China. Over the prior decade, the upheaval of the Cultural Revolution had disrupted scientific activity on a national scale. Yet after 1978, the sciences found an advocate in China's reformers. Broad-based economic reforms helped spur economic growth, which has in turn contributed to the growing funds available for research. Reforms also enabled biologists to access reagents and other materials necessary to conduct their experiments from national and international sources. Other policies focused specifically on boosting national competence in science and technology and led to funding increases, overseas

training opportunities for young scientists, and infrastructure improvements.

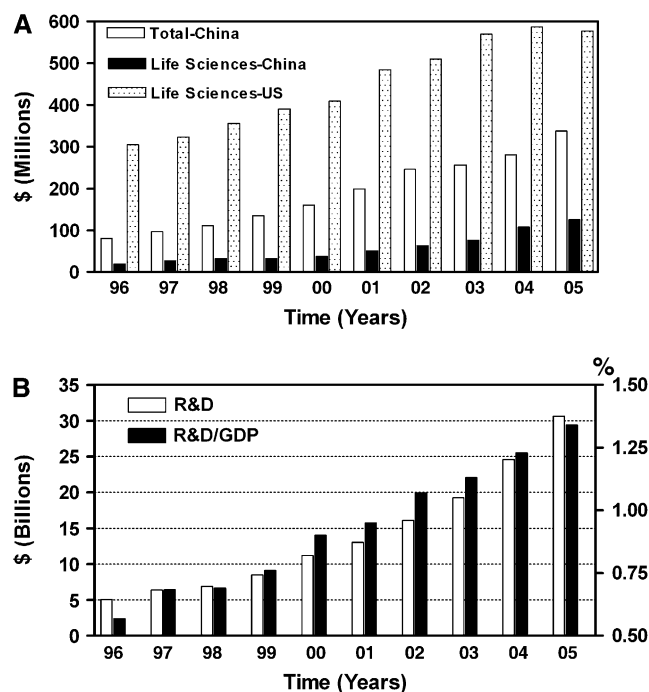
Funding for life sciences research has grown dramatically since reforms began. The budgets of the two major funding agencies that provide the main sources of support for plant biology, the National Natural Science Foundation of China (NSFC) and Chinese Ministry of Science and Technology, have grown significantly in the past two decades (Figure 2A; <http://www.nsfc.gov.cn>). As part of a long-term national strategy to raise basic and applied research capacity, life sciences research has been designated a key area for increasing future investment. As a percent-

age of total NSFC funding, the proportion budgeted for research in the life sciences has increased from 24 to 37% over the same period (i.e., from 19.6 million dollars in 1996 to 125.8 million dollars in 2005) (<http://www.nsfc.gov.cn>). On average, funding for research in the life sciences has increased by ~20% per year over the last 10 years. Total research and development funding, mostly from the Ministry of Science and Technology, has increased at >20% per year over the past decade. China's research and development funding as a proportion of GDP increased from 0.6% in 1996 to 1.3% in 2005 (Figure 2B; <http://www.most.gov.cn>). Local governments and other specialized agencies have also supported the development of plant biology research for agricultural or other applications.

Overseas training for young scientists has also been crucial to the revitalization of the plant sciences in China. Almost without exception, Chinese plant biologists currently engaged in notable and productive research have been trained or at least worked abroad—predominantly in North America, Western Europe, and Japan—after China launched its Open Door Policy in 1978. Many have since returned to China to take up full-time positions and establish research laboratories. Others retain their positions abroad but spend part of their time in China, where they oversee an independent research group of their own or a joint group with a local full-time faculty member. Those overseas experiences and resulting interpersonal and institutional connections have helped young scientists keep pace with the outside world, and there is an increased frequency of domestic and cross-border scientific exchange, both in terms of personnel visits and collaborations.

In addition to improving training opportunities for students, closer international ties have helped to upgrade the quality of scientific publications in China. The *Journal of Integrative Plant Biology* (formerly *Acta Botanica Sinica*), which is sponsored by the Institute of Botany (CAS) and the Botanical Society of China and launched its first publication in 1952, has been published by Blackwell in the United Kingdom since 2005. The *Journal of Plant Physiology* and

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**Figure 2.** Funding Trends in China over the Previous Decade (1996–2005).

**(A)** Trends in total and life sciences funding by the NSFC compared with life sciences funding by the U.S. National Science Foundation.

**(B)** The increase in research and development funding (in dollars) as a percentage of China's GDP over the last decade.

*Molecular Biology*, which has been sponsored by the Chinese Society for Plant Physiology and the Institute of Plant Physiology (CAS) beginning in 1964, will become an English-only journal starting in 2007 with a new name, *Plant Molecular Physiology*, published by Oxford University Press. Both journals used to be the major Chinese outlets for plant biology research and only published papers in Chinese. The internationalization of these journals is an encouraging development, given that publication in a journal published overseas with an overseas chief editor would have been unthinkable for many of China's scientists 10 years ago.

#### MAJOR PLAYERS IN PLANT RESEARCH IN CHINA

Institutional transformation during the reforms produced the facilities that today house most of China's plant biology re-

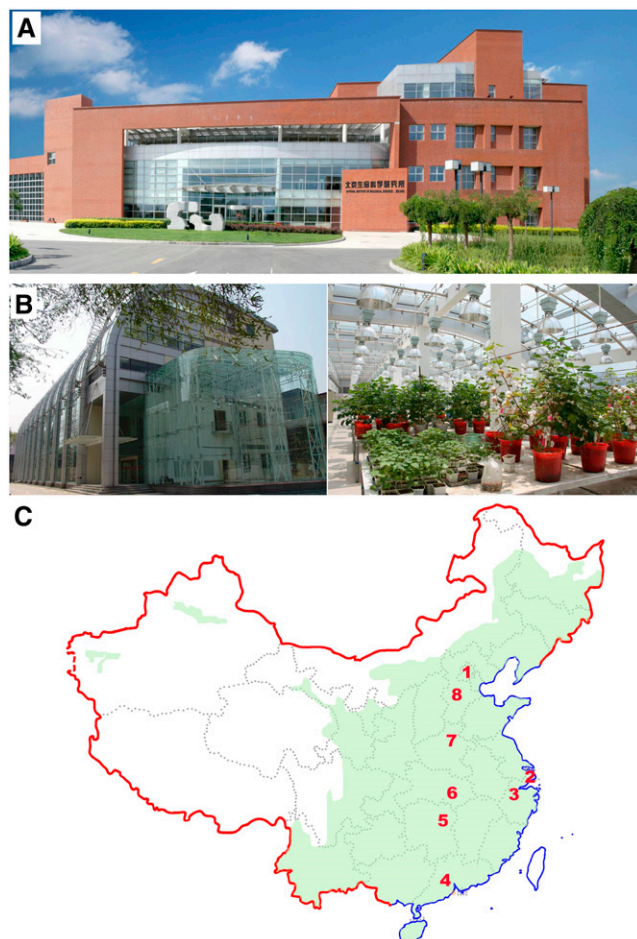
search. The Shanghai Institute of Plant Physiology and Ecology (SIPPE) was formed by the integration of the former Shanghai Institute of Plant Physiology and Shanghai Institute of Entomology, CAS, in 1999 (Figure 3B). Founded in 1944, the Shanghai Institute of Plant Physiology was one of the cradles of plant physiology research in China, and it contributed greatly to the establishment and expansion of molecular genetic research of plants and microorganisms. In particular, the institute has conducted notable research on photosynthesis and nitrogen fixation. After integration, research in SIPPE focused on functional genomics and molecular physiology of plants, microorganisms, and insects, plant-insect-microbe interactions, and molecular ecology. At the Institute of Plant Physiology and Ecology, scientists returning from overseas have provided the major driving force behind the institute's increase in research output. In the late

1990s, Xiaoya Chen (the current director), Hai Huang, and Da Luo comprised the first wave of new faculty recruits who had received advanced training abroad. The second major recruitment effort at this institute started in 2000, and a total of seven plant biology faculty members were recruited from overseas to the institute from 2000 to 2004. Most of these faculty members recruited in the last 10 years have made important contributions to their fields.

Another leading institute for plant biology research in China is the Institute of Genetics and Developmental Biology (IGDB), a CAS institute in Beijing. The IGDB was founded in 2001 by the merger of three former Institutes of CAS: The Institute of Genetics, The Institute of Developmental Biology, and The Shijiazhuang Agricultural Modernization Institute. Scientists in the IGDB work on both plant and animal models to address fundamental questions in the life sciences, focusing on areas such as genetic control of growth and development, gene expression, signal transduction, structural and functional genomics, and bioinformatics. Some researchers in the IGDB have also made significant progress on improving the water efficiency of agriculture and agronomic studies, with emphasis mainly on the improvement of crop productivity and quality. Jiayang Li, former director of the institute prior to his recent appointment as a vice president of CAS, returned to China in 1995 to launch his research program on the molecular basis of development in *Arabidopsis* and rice. Today, he is not only one of the leaders in the plant biology community, but also in the Chinese science community in general. A total of 11 plant biology faculty members have been recruited to this institute since 1995, and their research encompasses a wide range of areas.

Peking University, the former Jing Shi Da Xue Tang (the Imperial Capital University) of the Qing Dynasty, opened in December 1898. The plant biology research program in Peking University is among the earliest in Chinese universities. Its history can be traced back to October of 1905, when the College of Agriculture was founded on the campus of the former Jing Shi Da Xue Tang. Today, 37.5% of the principal

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**Figure 3.** Representative Institutions in China.

**(A)** The front view of NIBS in Beijing.

**(B)** The research greenhouse of the Institute of Plant Physiology and Ecology (CAS, Shanghai). An outside view is on the left, and a view from an inside corner is shown on the right.

**(C)** Most of the institutes and universities in plant biology discussed in this essay are located in eastern coastal regions of mainland China and major agricultural areas of the Yangtze Valley and North China Plain. Numbers mark sites of major institutes in Beijing (1), Shanghai (2), Zhejiang (3), Guangdong (4), Hunan (5), Hubei (6), Henan (7), and Hebei (8). The shadowed areas are the main agriculture lands in mainland China.

investigators at the College of Life Sciences are working in plant biology, most of whom received training abroad. Peking University has contributed to the large number of aspiring scientists trained in plant biology in China. Among them are the Peking University president Zhihong Xu and the newest returnee Hongwei Guo (who received his PhD from UCLA and postdoctoral training at the Salk Institute).

China Agricultural University (CAU) is a leading agricultural education and research institution in China, offering a wide range of subjects related to agriculture, including basic plant biology. CAU resulted from a merger of the former Beijing Agricultural University and Beijing Agricultural Engineering University in 1995. It was founded in 1949, when the College of Agriculture from Peking University, Tsinghua

University, and North China University merged and formed Beijing Agricultural University. Several notable research accomplishments resulted from faculty members who have returned after receiving training abroad. For example, Dapeng Zhang's group discovered a new receptor for the plant hormone abscisic acid (ABA) (Shen et al., 2006), and Wei-Hua Wu's group found that CIPK23, a member of the CIPK family, positively regulates the  $K^+$  transporter AKT1, particularly under low  $K^+$  stress (Xu et al., 2006).

These four institutions (all located in Beijing or Shanghai) are perhaps the finest examples of the progress that has been made in plant biology in China, and all have realized their success by following similar paths. First, the institutes and universities share a long experience with the plant sciences. Second, they have recruited talented and well-trained young prospects from abroad. Once the recruits had arrived, they were given ample support and time to develop their research programs. In most cases, new principal investigators were usually able to begin publishing in high-profile journals after 4 to 5 years. Almost all new recruits now in these four institutions have overseas training and remain competitive and connected with the global research community. Many other institutions beyond the four mentioned above have also shown impressive progress in developing strong plant biology programs, some of which are located in Hebei, Henan, Hubei, Hunan, Zhejiang, and Guangdong provinces (Figure 3C) and will be mentioned later.

Experimentation with new institutional models has become an important strategy for identifying successful systems of research funding and support. China has recently set up a new institute for basic research in the biological sciences with a strong plant biology component, the National Institute of Biological Sciences (NIBS) at Beijing (Figure 3A; [www.nibs.ac.cn](http://www.nibs.ac.cn)). Established with the full support of the Chinese leadership, NIBS serves as a new model for supporting and managing a basic research institution. The institute, under the leadership of its codirectors, Xiaodong Wang and Xing

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Wang Deng, operates independently without direct affiliation to any branch of government, giving it greater autonomy than traditional institutions, and is the first of its kind in China. The NIBS has its own governing body, the Board of Trustees, which comprises representatives of the related government branches and China's major scientific institutions and is responsible for institute policy and appointment of its directors. This new institute has recruited 14 full-time promising young faculty members from abroad since the first full-time faculty arrived in early 2004. At NIBS, individual research groups received full research funding for a term of 5 years, contingent upon satisfactory progress. This novel mechanism of funding support guarantees promising scientists full funding based on the quality of an applicant's past research and demonstrated capabilities. Researchers at NIBS have already shown their potential for accomplishment in their fields. A few recent examples include studies on the role of flagellin-induced defense in non-host resistance (Li et al., 2005c), a transcriptional analysis of the rice genome (Li et al., 2006b), and a description of a CUL4-based E3 ligase in light control of development (Chen et al., 2006). The inauguration of this institute is just one example of a larger trend toward granting greater autonomy and flexibility to scientific institutions in China.

## BREAKTHROUGHS IN RICE RESEARCH

It is hard to overestimate the importance of rice research in China, as the world's largest rice producer and consumer. China accounts for 23% of the world acreage in rice and 37% of world rice output in 2005. Domestically, rice supplies 40% of the dietary needs of the country's population of 1.3 billion (<http://www.chinariceinfo.com>). Longping Yuan, director of the China National Hybrid Rice Research and Development Center in Hunan Province, pioneered hybrid rice breeding and successfully developed the three-line hybrid rice breeding system in 1973. Hybrid rice now comprises ~50% of all commercially grown rice acreage and 58% of overall rice

production in China. In addition, there are about 2 million hectares of hybrid rice now grown in other Asian countries (Andrews, 2006). Yuan and his colleagues have consistently been improving hybrid rice breeding by seeking new and better germplasm and the development of new sterility lines for hybrid breeding technology. Recently, they have developed a two-line or super-hybrid breeding method to simplify and speed up the process of generating hybrid rice seeds (efficiency gains), which can lead to upward of 20% higher yield over three-line hybrid rice (<http://www.fao.org>).

Chinese scientists also made significant contributions to sequencing and functional analysis of the rice genome. Bin Han, who was recruited as the director of the National Center of Gene Research (CAS) in 1998 and is now the vice director of the Institute of Plant Physiology and Ecology, led the sequence analysis of *japonica* rice chromosome 4 as part of the international rice genome sequencing effort (Feng et al., 2002). The Beijing Genomics Institute (CAS), under the direction of several scientists, including Huanming Yang, Jun Yu, Jian Wang, and Jun Wang, produced a draft sequence of the rice genome for the most widely cultivated subspecies in China, *Oryza sativa* ssp *Indica* (Yu et al., 2002, 2005). The Beijing Genomics Institute, alone or as a participant in larger consortia, has since accomplished whole-genome sequencing of several other animals and has emerged as an important player in genome research globally. In subsequent work on sequence analysis of the rice genome, they identified extensive retrotransposition and provided strong evidence that retrotransposition is an important mechanism of gene evolution in rice and other grass species (Wang et al., 2006a). In a close collaboration with the Peking-Yale Joint Center of Plant Molecular Genetics and Agrobiotechnology, the first whole-genome microarray of rice was developed and used in profiling the genome expression patterns during rice development (Ma et al., 2005).

Furthermore, a number of agronomically important rice genes have been cloned and characterized by Chinese scientists. Jiayang Li's group in the IGDB have isolated and characterized the rice *MONO-*

*CULM1* (*MOC1*) gene, which plays a critical role in controlling rice tillering and is a major determinant of rice grain yields. Their work revealed that *MOC1* is specifically expressed in the axillary buds and is essential for their initiation and outgrowth (Li et al., 2003a). In another study, they reported that mutations in the rice *BRITTLE CULM1* gene cause not only a reduction in cell wall thickness and cellulose content but also an increase in lignin in developing sclerenchyma cells, which provide the mechanical strength of rice plants (Li et al., 2003b). At SIPPE, Hongxuan Lin's group isolated the rice *SKC1* gene by map-based cloning and found that the SKC1 protein works as a HKT-type transporter and plays a key role in the regulation of  $K^+/Na^+$  homeostasis under salt stress, making it a potential molecular target for improving salt tolerance in crop plants (Ren et al., 2005). Qifa Zhang, Shiping Wang, and their colleagues at Huazhong Agricultural University have contributed significantly to the fields of genome evolution, biotechnology development, and functional genomics of rice. A number of their studies have focused on the organization and evolution of the rice genome by analyzing the distribution and copy number of copia-like retrotransposons in rice (Wang et al., 1999), assessing syntenic relationships of quantitative trait loci for disease resistance in cereals (Chen et al., 2003) and investigating the genetic basis of heterosis in an elite rice hybrid (Hua et al., 2003). The most recent example of their work deals with plant-pathogen interactions and pollen development (Chu et al., 2006). At South China Agricultural University, an exciting discovery from Yao-Guang Liu's laboratory recently helped to elucidate the mechanism underlying the function of rice cytoplasm fertility restorer genes (Wang et al., 2006b); this work has significant implications for hybrid rice breeding. At Zhejiang University, Ping Wu and colleagues recently reported the first genetically defined function of a plant glutamate receptor in cell division and individual cell survival in the root apical meristem (Li et al., 2006a). Zuhua He's group at SIPPE demonstrated that the rice *UPPERMOST INTERNODE* locus, which when overexpressed causes

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short plant stature, encodes a gibberellin-inactivating enzyme (Zhu et al., 2006), revealing the molecular basis of a key agronomic trait.

### RAPID GROWTH OF *ARABIDOPSIS* RESEARCH

Before 1995, no Chinese scientists were doing internationally acknowledged research using the model plant *Arabidopsis*. Today, almost every major institute or university with a plant biology research program has multiple *Arabidopsis* groups, an indication that Chinese plant biologists now value both the basic and applied research in crop plants. Within the last decade, encouraging progress in *Arabidopsis* research has been achieved in China. Following is a brief overview of progress in key subfields.

#### Hormonal Signaling

At Peking University, Li-Jia Qu and colleagues found an indole-3-acetic acid (IAA) carboxyl methyltransferase (IAMT1) that has the ability to convert IAA into methyl-IAA ester in the regulation of auxin homeostasis (Qin et al., 2005). This discovery was made based on the initial observation that changing expression patterns of IAMT1 often cause dramatic leaf curvature phenotypes, providing a better understanding of auxin regulation of development. Jiayang Li's group also identified a role for the mitogen-activated protein (MAP) kinase cascade in auxin signaling by observing that the semidominant *Arabidopsis bud1* mutant defective in the *MAPKK7* gene displays pleiotropic phenotype characteristics of auxin deficiency syndrome and demonstrating that the *BUD1/MAPKK7* gene negatively regulates polar auxin transport (Dai et al., 2006). Xiaoya Chen's group showed that the *Arabidopsis* microRNA160, which targets transcripts encoding auxin response factors (*ARF10* and *ARF16*), controls root cap cell formation (Wang et al., 2005).

Studies on ABA signaling in China also yielded important results. Although the RNA binding protein FCA has been reported as an ABA receptor involved in ABA-mediated control of flowering time, it is not the recep-

tor for other known ABA responses (Razem et al., 2006). As mentioned earlier, Dapeng Zhang and colleagues at CAU recently reported the discovery of another possible ABA receptor candidate, the chloroplast-located Mg-chelatase H subunit, which is involved in ABA responses such as seed germination and stomatal aperture movement (Shen et al., 2006). Hongwei Xue's group found that brassinosteroids can both alter the expression of *PIN* genes and promote the functional localization of the PIN2 protein modulated by a Rho-related GTPase (ROP2), indicating that brassinosteroids promote plant tropisms by modulating polar auxin transport (Li et al., 2005b).

#### Light Regulation of Development

A joint research group under the Peking-Yale Joint Research Center of Plant Molecular Genetics and Agrobiotechnology, in which two of the authors of this article are involved, profiled *Arabidopsis* genome expression under different light conditions and in various mutant backgrounds, allowing for a genome-wide analysis of the factors and pathways involved in mediating light control of *Arabidopsis* development (Ma et al., 2001, 2002, 2003). Another recent study by Hongquan Yang's group at SIPPE revealed that the dimerization of the blue light photoreceptor CRY1 plays a key role in triggering the cryptochrome 1 (CRY1) signaling pathway (Sang et al., 2005). They also reported that CRY1 functions additively with phototropins (PHOT), another blue light receptor, to mediate blue light-induced stomatal opening, and that the CRY1-PHOT signaling pathways likely act upstream of COP1, which is a repressor of stomatal opening (Mao et al., 2005). These discoveries have furthered our understanding of the function of CRY1, a highly conserved and critical light sensor. Lixin Zhang's group at the Institute of Botany (Beijing), CAS, has further presented an important discovery in the regulation of the photosystem II complex assembly (Peng et al., 2006).

#### Stress Responses

Research on plant response to stresses (such as salt, cold, UV, or drought) in

*Arabidopsis* can aid in the development of strategies for agriculture improvement. At the China Agricultural University, Wei-Hua Wu's group has made exciting progress in the area of plant signal transduction and resistance to abiotic stresses. This is exemplified by their recent report in *Cell* on CIPK23, a member of the CIPK family that positively regulates the K<sup>+</sup> transporter AKT1, particularly under low K<sup>+</sup> stress (Xu et al., 2006). In addition, they found that CBL1 and CBL9, two calcineurin B-like proteins, work as positive upstream regulators of CIPK23. Their working model indicates that low K<sup>+</sup> stress signals can trigger the cytosolic Ca<sup>2+</sup> signal and activate the calcium sensors CBL1 and CBL9 in the plasma membrane. The CBL proteins interact with CIPK23 and can recruit CIPK23 to the plasma membrane, where AKT1 is phosphorylated by CIPK23. Thus, under low K<sup>+</sup> conditions, AKT1 is activated for K<sup>+</sup> uptake. It is noteworthy that CIPK23 might also regulate other K<sup>+</sup> transporters besides AKT1 (Xu et al., 2006). Chun-Peng Song's group at Henan University found that mutants of *Arabidopsis GLUTATHIONE PEROXIDASE3 (ATGPX3)* exhibited a higher rate of water loss under drought stress, higher sensitivity to H<sub>2</sub>O<sub>2</sub> treatment during seed germination and seedling development, and enhanced production of H<sub>2</sub>O<sub>2</sub> in guard cells, while the overexpressing plants showed the opposite phenotype. Further analyses suggest that ATGPX3 might act as a scavenger, specifically relaying the H<sub>2</sub>O<sub>2</sub> signal as an oxidative signal transducer in ABA and drought stress signaling (Miao et al., 2006).

#### Regulation by Chromatin and MicroRNA

Epigenetic control of plant development has emerged as a major focus of plant biology research in recent years. Xiaofeng Cao, a faculty member at the IGDB, examined the role of the *DRM* and *CMT3* DNA methyltransferase genes in the initiation and maintenance of RNA-directed DNA methylation. She and other colleagues revealed that *DRM* and *CMT3* act redundantly to maintain non-CpG methylation, downstream of small interfering RNA action (Cao et al., 2003). At the China

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Agriculture University, a group led by Zhizhong Gong has revealed critical roles for a putative DNA replication protein in epigenetic gene silencing (Xia et al., 2006). This work revealed a possible link between DNA replication and the regulation of gene expression, thus establishing a new function for this class of DNA replication proteins. At SIPPE, Hai Huang's group demonstrated that the *Arabidopsis* AS1 and AS2 genes are critical for specifying leaf adaxial-abaxial polarity using mutant alleles that display insightful phenotypes (Xu et al., 2003). Their genetic analysis of leaf development further revealed that the *Arabidopsis* RDR6-associated epigenetic pathway and the AS1-AS2 pathway work in concert to repress *BREVIPEDICELLUS* and microRNA165/166 (Li et al., 2005a) and that the 26S proteasome is also required for normal leaf polarity (Huang et al., 2006), both functions that were previously unknown. In a study of *Arabidopsis* root development, Shunong Bai's group at Peking University revealed that the expression of the genes controlling the epidermal cell identity was regulated through a positional cue mediated by histone acetylation (Xu et al., 2005).

### Reproductive Development

Wei-Cai Yang, who moved his research program from Singapore to the CAS Institute of Genetics and Developmental Biology in 2002, has recently reported the functional characterization of specific genes essential for gametogenesis (Shi et al., 2005) and early embryogenesis in *Arabidopsis* (Ding et al., 2006). Those studies provide novel insights into the developmental roles of genes that also perform basic cellular functions, such as transcription and translation.

### NEW DISCOVERIES IN OTHER PLANT SYSTEMS

The first article in *The Plant Cell* from a laboratory based in China, that of Daye Sun at Hebei Normal University, focused on the role of the heterotrimeric G protein in pollen development in lily (Ma et al., 1999). Other plants, such as cotton and *Antirrhinum*, have also been the subject of major

research by Chinese scientists. For example, Xiaoya Chen's group discovered a secreted enzyme that can catalyze the oxidation of a broad range of phenolic compounds that are among the most hazardous and recalcitrant pollutants in the environment (Wang et al., 2004a), suggesting a potential detoxification strategy. In another report, they presented molecular studies supporting the idea that cotton and *Arabidopsis* use similar transcription factors to regulate trichome development and that GaMYB2 may play a key role in regulating cotton fiber development (Wang et al., 2004b). These results suggested new strategies for genetic engineering of cotton fiber. Through EST sequencing of a cotton fiber cDNA library and subsequent microarray analysis, Yuxian Zhu's group found that the ethylene biosynthesis pathway was significantly upregulated during fiber elongation and concluded that ethylene plays a major role in promoting cotton fiber elongation by promoting cell elongation (Shi et al., 2006).

Another productive laboratory at the IGDB is headed by Yongbiao Xue, its current director, who was recruited in 1998. Yongbiao Xue's group has performed a series of interesting studies on the molecular mechanisms of self-incompatibility. In particular, his group discovered the S-locus F-box protein gene and showed that the *Antirrhinum* S-locus F-box protein Ah-SLF-S<sub>2</sub> can form a SCF(AhSLF-S<sub>2</sub>) complex to target S-RNase destruction during compatible pollination but not during incompatible pollination (Qiao et al., 2004a). This line of study suggested a biochemical basis for discrimination between self and non-self in the *Antirrhinum* self-incompatible response. Further analysis using transgenic petunia plants demonstrated that the polymorphic SLFs, including AhSLF-S<sub>2</sub>, control the pollen function of the *Antirrhinum* S-RNase-based self-incompatibility system (Qiao et al., 2004b). Da Luo's group at the SIPPE demonstrated that *CYCLOIDEA* homologues have been independently recruited to determine petal identities along the dorsoventral axis in two distant lineages of flowering plants (*Antirrhinum majus* and *Lotus japonicus*) (Feng et al., 2006). They revealed that highly similar molecular

mechanisms controlling floral bilateral symmetry can originate in separate groups of plants with radial symmetry (Feng et al., 2006), suggesting that there might be a limited number of possible mechanisms underlying zygomorphy.

### CHALLENGES

Despite these promising developments, China's modern plant biology research is in many respects still in its adolescence. In terms of research funding and output, China still lags behind many of the advanced industrialized countries, where modern plant biology research programs are far more established. There is great potential for further improvement in China, both in terms of research output and the environment for conducting plant biology research. When publication records for China and the U.S. are compared, the gap in output becomes clear. In *The Plant Cell*, China published 13 articles in the first 11 months of 2006, while the U.S. published 60. There is an even larger gap if the publications in the more general journals, such as *Nature*, *Science*, and *Cell*, are compared. Another challenge will be encouraging the contribution of female scientists, who have been underrepresented in plant sciences research in China.

As pointed out earlier, the funding for the life sciences in China is still relatively low compared with the developed countries in both the total dollar amount (Figure 2A) and the percentage of domestic GDP allocated to research and development. The overall research and development budget of China only accounts for 1.3% of the GDP, while most advanced industrialized countries with well-developed plant science research programs allocated ~2.5% of their GDP to research and development in 2005. As the country with the world's fourth largest GDP, China still has great room for improvement when directly compared with the countries with the first and third largest GDP (the U.S. and Germany, respectively) (GDP data come from the World Development Indicators database, World Bank, July 1, 2006). When comparing publications in *The Plant Cell*, China still lagged

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behind Germany, which is much closer to China in terms of GDP than the U.S. Compared with China's 13 articles so far in 2006, Germany published 36, or more than twice as many.

Scientists and outside observers have pointed out that present evaluation systems for research proposals and institutional/individual performance are in need of significant modernization. The independent peer review model widely used in developed countries needs to be implemented at every level of the scientific evaluation system in China. Furthermore, the present evaluation system is typically based heavily on short-term productivity rather than long-term discovery. A more patient and balanced evaluation system on the institutional and personal productivity would likely promote risk-taking in the search for major scientific breakthroughs in the long run.

## FUTURE TRENDS

Although challenges remain, China has made strides toward its long-term goal of modernizing its scientific enterprise. In plant biology, these efforts are perhaps most evident in the increased funding allocations, support for returning scientists, infrastructure improvements, and the strengthening of institutions and the university system. Government policies enacted during the reforms have set in motion a wave of institutional transformation and willingness to experiment that is likely to have profound effects on the way science is conducted in China by helping leaders to identify what models work best. The accomplishments of the many scientists described in this essay and others suggest that many institutes—both new and old—are growing capable of conducting research that is internationally recognized as valuable to the field.

Increased reform and openness in China have enabled Chinese scientists to take advantage of a broader trend toward the globalization of scientific research. Beyond attracting Chinese nationals, many institutions are interested in hiring the best talent regardless of nationality, and a few non-Chinese nationals have already worked in various CAS institutes. Hiring of non-Chinese nationals can be expected to in-

crease as China's research environment becomes increasingly attractive. In contrast with the conventional perception, long-term employment of non-Chinese nationals was not uncommon throughout the Chinese history, although it was suspended for ~30 years (1950s–1980s). Today, employment of non-Chinese nationals in both the public and private sectors is again common in China. For example, a prominent nationality-blind program established by the Chinese government, the Changjiang Visiting Scholarship of the Education Ministry, has provided both research funding and living/travel allowance for scientists around the world to do research in Chinese universities. Many universities and institutes are ready to hire on the basis of qualifications, regardless of nationality, in the interest of developing China's research laboratories into truly international centers of excellence.

Funding for both basic and applied research in China is further expected to grow. In recent years, the funding allocated to basic research has increased, and current policies indicate that this trend will continue. Since the question of how to feed 1.3 billion mouths on only a modest and shrinking area of available arable land ranks among the top concerns of China's leadership, funding for applied agricultural sciences and biotechnology is also expected to remain substantial for the foreseeable future. However, funding alone may not be sufficient to close the gap with advanced industrialized countries; the additional challenges listed above will also need to be addressed if China is to develop a truly world-class research environment. Still, signs of great progress in plant science research abound and should only embolden scientists and leaders to tackle the remaining challenges.

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